

Short Communication

Influence of Socioeconomic Factors and Energy Supply Structures on Air Quality: a Case Study in Shandong Province, North China

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Abstract

Currently, air pollution becomes a wide-concerned global environmental problem. In Shandong Province of North China, the air quality deterioration has greatly restricted the development of society and threatened human health. In this study, air quality index (AQI) and 6 pollutants monitored in 2019 are analyzed associated with socioeconomic factors, aiming to identify the characteristics and driving factors of air pollution. Our results show that great seasonality and spatial heterogeneity exists for AQI and pollutants. The variation patterns result from mechanisms of pollutants formation, and are mainly dependent on the coal burning-dominated energy production and climatic periodicity. Correlation analysis shows that AQI decreases with the increase of factors of city size, resource and energy consumption, transportation and economy, but is weakly related to population. The ratio of energy supply for different purpose also influences the air pollutants. The increased proportion of electric supply for productive use will result in anabatic pollution caused by particle matters, oxynitrate and oxysulfide. This study provides useful information for the better control of air pollution and insights for the making of environmental-friendly strategies for energy supply.

Keywords: pollutant emissions, spatio-temporal variability, socioeconomic factors, energy supply ratio

Introduction

Under the background of global climate change and intensive anthropogenic activities, air pollution has become one of the most severe global environmental

issues [1, 2]. In urban areas, the deterioration of air quality hinders social operation and threatens the health of susceptible people, such as the older and infants [3]. In order to better understand the mechanisms of air quality deterioration and take efficient measurements to control the air pollution, it is important to set up relationship between the concentrations of pollutants and different potential drivers, and identify the main controls at different spatial scales [4, 5].

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Air quality is a result of multiple natural and anthropic processes. In previous studies, it has been proved that socioeconomic factors are major explanatory variables of the quality in the current world [6-8]. According to Environmental Kuznets Curve, the relationship between environmental quality and economy can be divided into different stages, which is mainly dependent on the structure of incomes of a society [9]. Factors such as population, urban land area and industrial structure have important influences on the air quality [10, 11]. Compared with rural area, the spatio-temporal evaluation of air quality in urban area is more complicated, where lots of driving factors overlap with each other, especially in developed metropolitans.

Energy use and transportation are main sources of air pollutants, which are closely related to the local patterns of social and economic development. Generally, the energy consumption is positively correlated with the level of regional economy, but the effect of energy consumption on air quality varies between regions [12-14]. In developed countries and regions, the wide use of cleaner fuels and proven technologies of cleaner production promotes the efficiency and reduces the emission of waste gas. Reversely, backward technologies and low energy production efficiency is universe in undeveloped countries and regions, leading to anabatic air pollution. However, to our knowledge, it has not been revealed if there's a relationship between the air quality and ratio of energy supply for different purposes.

During the past few decades, China has experienced fast economic development, which has accelerated the urbanization and industrialization to a great extent. The increasing population, associated with increasing number of vehicles and amount of energy consumption,

leads to the massive emission of pollutants into the atmosphere. Shandong Province is characterized by highest population density and most developed industry and agriculture in North China. The fast growth of urbanization and industrial production has resulted in high emission of atmospheric pollutants and led to serious health risks of residents in this area [15-17]. Under the background illustrated above, the objectives of this study are as follows: (1) to delineate the characteristics of air quality variation in Shandong Province, (2) to identify the main socioeconomic controls on air quality and (3) to determine how the energy supply structure influences the concentrations of pollutants.

Methods and Materials

Study Area

Shandong is located in the northern and eastern part of China. The eastern coastal area of Shandong belongs to Shandong Peninsula and the western inland area belongs to North China Plain. It has a population of 101.5 million and land area of 1.558×10^6 km². The gross regional product (GRP) ranks 3-rd among all provincial administrative districts in China, and it shows a fast annual growth. Shandong is rich in coal resources, which account for more than 75 % of the total energy source consumption in this province. Almost 100 % of electricity is generated by coal-burning plants. Overall, coal utilization technology is relatively backward. Direct combustion of raw coal is used for electric production in most plants, and facilities for desulfurization and dust removal are not

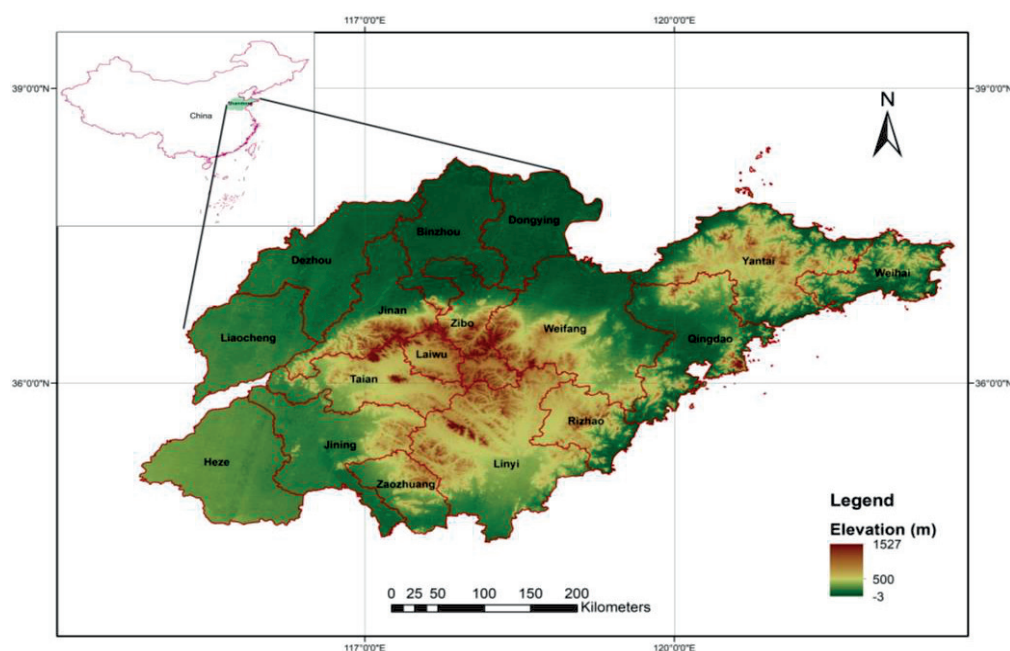


Fig. 1. Geographical location, topography and city distribution of Shandong Province.

used in many small plants. As coal is a main source of many air pollutants, such as SO₂, NO₂ and dust, the coal-dominated energy structure leads to severe air pollution problems in Shandong Province.

Source of Data

AQI is a comprehensive parameter used for the assessment of air quality. It is a dimensionless index that describes the concentrations of atmospheric pollutants, including PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃. Higher value and category of AQI indicate worse air quality condition and more serious risks to human health. According to the guidebook for Environmental Air Quality Evaluation (HJ663-2013) published by the Ministry of Ecology and Environment of China, the daily air quality can be classified into 6 categories based on the AQI values: Class I (≤50), Class II (51~100), Class III (101~150), Class IV (151~200), Class V (201~300) and Class VI (≥301). In our present work, the AQI and concentrations of air pollutants are sourced from the data center of the Ministry of Ecology and Environment of China (<http://datacenter.mee.gov.cn/websjzx/queryIndex.vm>) and the air quality online monitoring and analysis platform (<https://www.aqistudy.cn>).

To identify the main controlling factors, 13 socioeconomic factors of cities are selected as explanatory variables of air quality, which belong to classifications of city size, environment protection, economy, transportation and energy and resource consumption. Factors related to city size include population (POP) and urban land area (ULA); that

related to environmental protection is green land area (GLA); those related to economy include per capita gross domestic product (PCGDP), percentage of primary industrial to GDP (PPI), percentage of secondary industrial to GDP (PSI) and percentage of tertiary industrial to GDP (PTI); those related to transportation are highway freight traffic amount (HFT), per capita annual transportation by bus (PCPTB) and area of city paved roads (ACPR); and those related to energy and resource consumption include water supply (WS), total gas supply (TGS) and annual electricity consumption (AEC). The selected factors are annual data of the year 2019, collected from the China Urban Statistical Yearbook published by the National Bureau of Statistics of China (<http://www.stats.gov.cn/>).

Results and Discussion

Spatial and Temporal Variations of Air Quality

The annual ranges of AQI in 17 cities of Shandong province are shown in Fig. 2. The AQI value shows great spatial heterogeneity and annual ranges in cities of Shandong province. The highest mean AQI is observed in Laiwu, whose average value reaches 141.5 and the highest value is up to 395. Annual averages higher than the threshold of Class III (i.e., 100), which represents the mild contamination condition, are observed in Heze (101.1) and Liaocheng (100.3). The air quality can be considered to remain at an overall harmful level in these 3 cities. All of them are located in Western inland area of Shandong Province. The lowest mean AQI of 62.9 is

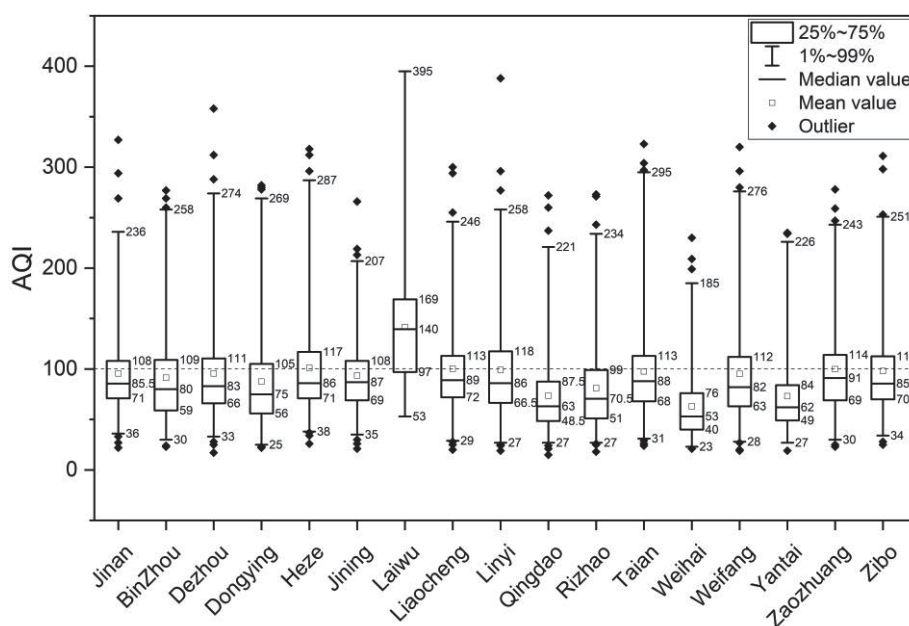


Fig. 2. Boxplot showing the spatial difference of AQI in the observation year of 2019. The lines of the box plot represent the values of upper, median and lower quartiles. The whiskers represent the 1-st and 99-th percentiles. The squares inside the box represent the mean values.

observed in Weihai, followed by Yantai (73.1), Qingdao (73.6), Rizhao (81.0) and Dongying (87.6). These cities are all located in the coastal area. Among the 17 cities in Shandong Province, the AQI values of upper quantile are observed to be lower than 100 in only 4 cities (i.e., Weihai, Yantai, Rizhao and Qingdao), indicating that people were faced with health risk for more than 25 % of days in most cities.

Global Moran's I is an important metric used to measure spatial correlation. The metric has a range from -1 to +1. When Moran's I is greater than 0, it means that the data show positive spatial correlation, and the value is positively related with spatial correlation. When Moran's I is less than 0, it means that the data show negative spatial correlation, and the smaller the value the larger the spatial difference; when Moran's I is 0, the spatial distribution is random. The P value of Moran's I indicates the probability. When P is small, it means that the observed spatial pattern is unlikely to arise from a random process. Z value indicates the standard deviation multiplier, which reflects the dispersion of a data set. Global autocorrelation analysis is conducted based on the data of AQI of cities in Shandong Province in 2019. The results show that the Global Moran's I value is 0.28, the z value is 1.96, with a P value of 0.05. The positive Global Moran's I value exhibits with a significance at 0.05 confidence level indicates that the AQI of cities in Shandong province shows a significant positive correlation. The spatial pattern of air quality in Shandong province has a pronounced aggregation, with highly polluted areas tending to be adjacent to areas with high AQI and vice versa. Because of the mobility of air, the air quality of a city is not only a function of local conditions, but also influenced by those of adjacent cities.

As shown in Fig. 3a), the monthly average value of AQI shows clear seasonality. The valley is observed in August, and the peak is observed in January. Variation patterns of ratios of Class I and II is in contrast with that

of AQI. The highest value is observed in August and the lowest one is observed in January. Except for O_3 , other pollutants present similar patterns of seasonality, whose concentrations are low in summer and high in winter (shown in Fig. 3b). In northern China, massive smog related to coal-fired heating in winter months are the anthropogenic sources of many atmospheric pollutants, explaining the air quality deterioration and increased concentrations. However, O_3 presents high concentrations in summer months and low ones in winter months. O_3 is a secondary pollutant derived from complex photochemical reactions of primary pollutants such as volatile organic compounds (VOCs), nitrogen oxides (NOx) and CO emitted by human activities under sunlight. In summer, strong solar radiation and hot weather are conducive to the production of O_3 .

Influence of Socio-Economic Attributes on Air Quality

The Pearson's correlation coefficients (r values) between AQI and socioeconomic factors are shown in Fig. 4. In Shandong province, a strong negative correlation is observed between AQI and PCGDP, indicating that better economic level is associated with worse air quality. In the early stage of urban economic development, the growth of PCGDP is accompanied by the advancement of industrialization and resource consumption, which has a negative effect on air quality. The sustained economic growth has a propulsive effect on technological progress, upgrading of industrial structure and environmental management, which helps to reduce pollutant emissions and improve air quality. Our results indicate that Shandong province has a high level of economic development and the relationship between urban air quality and economic growth is on the right side of the inflection point of the environmental Kuznets curve (EKC), where economic growth promotes air quality improvement. It is also

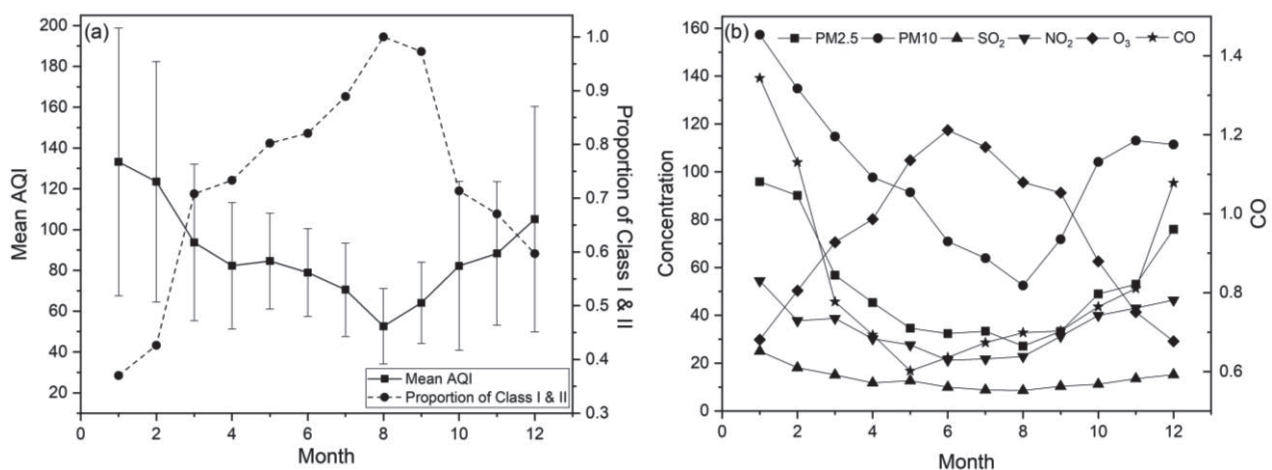


Fig. 3. Monthly variation of a) averages and standard errors of AQI and ratios of Class I and II in 2019, and b) average concentrations of 6 monitored pollutants.

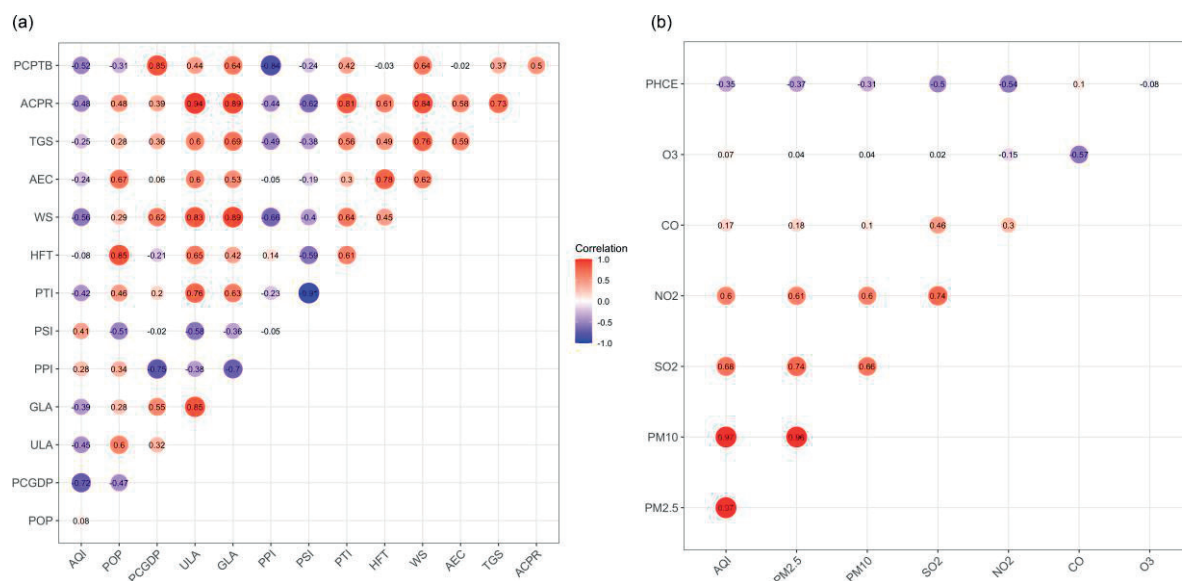


Fig. 4. Matrix showing the Pearson Rank Correlation between a) the socioeconomic parameters and AQI, and b) proportion of household-consumed electricity (PHCE) and concentrations of pollutants.

observed that AQI exhibits a moderate ($0.3 < r < 0.6$) negative correlation with ULA, GLA, WS, PCPTB and ACPR. All of these factors present a moderate or high positive correlation ($r > 0.3$) with PCGDP. This suggests that economic growth will be accompanied by the city expansion, enhanced environmental protection, transportation construction and increased consumption of resources, which shows positive effect on the air quality improvement. The economic contribution of primary (PTI) and secondary (PSI) industries are only factors that are positively correlated with AQI, indicating that activities of industrial and agricultural production are the main factors exacerbating air pollution.

Although population (POP) shows moderate to strong correlation with variables related to city size (ULA), energy consumption (AEC), transportation (ACPR, HFT, PCPTB) and economy (PPI, PSI, PTI, PCGDP), it almost exhibits no correlation with AQI, indicating that population aggregation is not the dominant cause of air quality changes in Shandong Province. Weak negative correlations are observed between AQI and AEC, and almost no correlation exists between AQI and HFT ($r < 0.1$). Both of them show strong correlations with population ($r \geq 0.6$). This indicates that the increase in energy and resource consumption and traffic volume due to population aggregation has a slight impact on air quality.

Influence of Energy Supply Structure on Air Quality

Based on the purposes, the consumption of energy can be classified into 2 categories of productive uses and household uses. The ratio of the consumption amount between these two purposes can be considered

to be an integrated reflection of energy supply structure. The proportion of household-consumed electricity (PHCE) is calculated and used to establish the relationship between AQI (shown in Fig. 4b). PHCE presents moderate negative correlations ($0.3 < r < 0.6$) with AQI, $PM_{2.5}$, PM_{10} , SO_2 and NO_2 , but shows very weak correlations ($r < 0.1$) with CO and O_3 . This indicates that the higher proportion of production-used electricity will lead to more severe air pollution, which is derived from the emission of oxysulfide, oxynitrate and particle matters. PHCE shows highest absolute r values with SO_2 and NO_2 , suggesting that the increase of energy consumption in productive activities is associated with increased emission of SO_2 and NO_2 .

Conclusions

Based on the monitored AQI and concentrations of atmospheric pollutants in 2019, this study reports the spatio-temporal characteristics of air quality and determines its main controls in Shandong Province of China. AQI shows an obvious spatial heterogeneity. Better condition is observed in coastal area and worse one is observed in inland area. AQI and all 6 pollutants present seasonal variability, resulting from both natural process and periodicity of energy production. Pearson rank correlation shows that air quality is controlled by parameters related to urban size, energy consumption and economy, but less affected by the population aggregation. The structure of energy supply also has an influence on the air quality. Higher proportion of production-used energy will be more prone to cause air quality deterioration, especially for the increased concentrations of SO_2 and NO_2 .

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Conflict of Interest

The authors declare no conflict of interest.

References

1. ARMENTA S., DE L.A. GUARDIA M. Pollutants and Air Pollution. *Comp Anal C*, **73**, 2016.
2. CHAN C.K., YAO X. Air pollution in mega cities in China. *Atmos Environ*, **42**, 1, 2008.
3. GURJAR B.R., JAIN A., SHARMA A., AGARWAL A., GUPTA P., NAGPURE A.S., LELIEVELD J. Human health risks in megacities due to air pollution. *Atmos Environ*, **44**, 36, 2010.
4. CETIN M. The effect of urban planning on urban formations determining bioclimatic comfort area's effect using satellitia imagines on air quality: a case study of Bursa city. *Air Qual Atmos Hlth*, **12**, 10, 2019.
5. FANG C.L., WANG Z.B., XU G. Spatial-temporal characteristics of PM_{2.5} in China: A city-level perspective analysis. *Journal of Geographical Sciences*, **26**, 11, 2016.
6. ARTINANO B., SALVADOR P., ALONSO D.G., QUEROL X., ALASTUEY A. Anthropogenic and natural influence on the PM₁₀ and PM_{2.5} aerosol in Madrid (Spain). Analysis of high concentration episodes. *Environ Pollut*, **125**, 3, 2003.
7. BEN SAAD M. The Effect of Economic Complexity on Air Pollution: Another approach to the Environmental Curve of Kuznets. *Rev Dev*, **46**, 2017.
8. HE K.B., HUO H., ZHANG Q. Urban air pollution in China: Current status, characteristics, and progress. *Annu Rev Energ Env*, **27**, 2002.
9. GROSSMAN G.M., KRUEGER A.B. Economic-growth and the environment. *Quarterly Journal of Economics*, **110**, 2, 1995.
10. LIU H.M., FANG C.L., ZHANG X.L., WANG Z.Y., BAO C., LI F.Z. The effect of natural and anthropogenic factors on haze pollution in Chinese cities: A spatial econometrics approach. *J Clean Prod*, **165**, 2017.
11. WEI F.L., LI S., LIANG Z., HUANG A.Q., WANG Z., SHEN J.S., SUN F.Y., WANG Y.Y., WANG H., LI S.C. Analysis of Spatial Heterogeneity and the Scale of the Impact of Changes in PM_{2.5} Concentrations in Major Chinese Cities between 2005 and 2015. *Energies*, **14**, 11, 2021.
12. LI L., HONG X.F., WANG J. Evaluating the impact of clean energy consumption and factor allocation on China's air pollution: A spatial econometric approach. *Energy*, **195**, 2020.
13. LIN H., CHEN H.X., ZHANG L., LUO Y.J., SHI Y., ZOU W.J. Energy consumption, air pollution, and public health in China: based on the Two-Stage Dynamic Undesirable DEA model. *Air Qual Atmos Hlth*, **14**, 9, 2021.
14. TSUJIMOTO M. Economic Growth and Air Pollution in the Persian (Arabian) Gulf States: Environmental Kuznets Curve Hypothesis. *J Jpn I Energy*, **97**, 1, 2018.
15. FAN W.P., WANG H.K., LIU Y., LIU H.P. Spatio-temporal variation of the coupling relationship between urbanization and air quality: A case study of Shandong Province. *J Clean Prod*, **272**, 7, 2020.
16. JIANG B.W., LI Y.G., YANG W.X. Evaluation and Treatment Analysis of Air Quality Including Particulate Pollutants: A Case Study of Shandong Province, China. *Int J Env Res Pub He*, **17**, 24, 2020.
17. ZHOU M.M., JIANG W., GAO W.D., GAO X.M., MA M.C., MA X. Anthropogenic emission inventory of multiple air pollutants and their spatiotemporal variations in 2017 for the Shandong Province, China. *Environ Pollut*, **288**, 5, 2021.